

## 6. POTENTIAL FOR HUMAN EXPOSURE

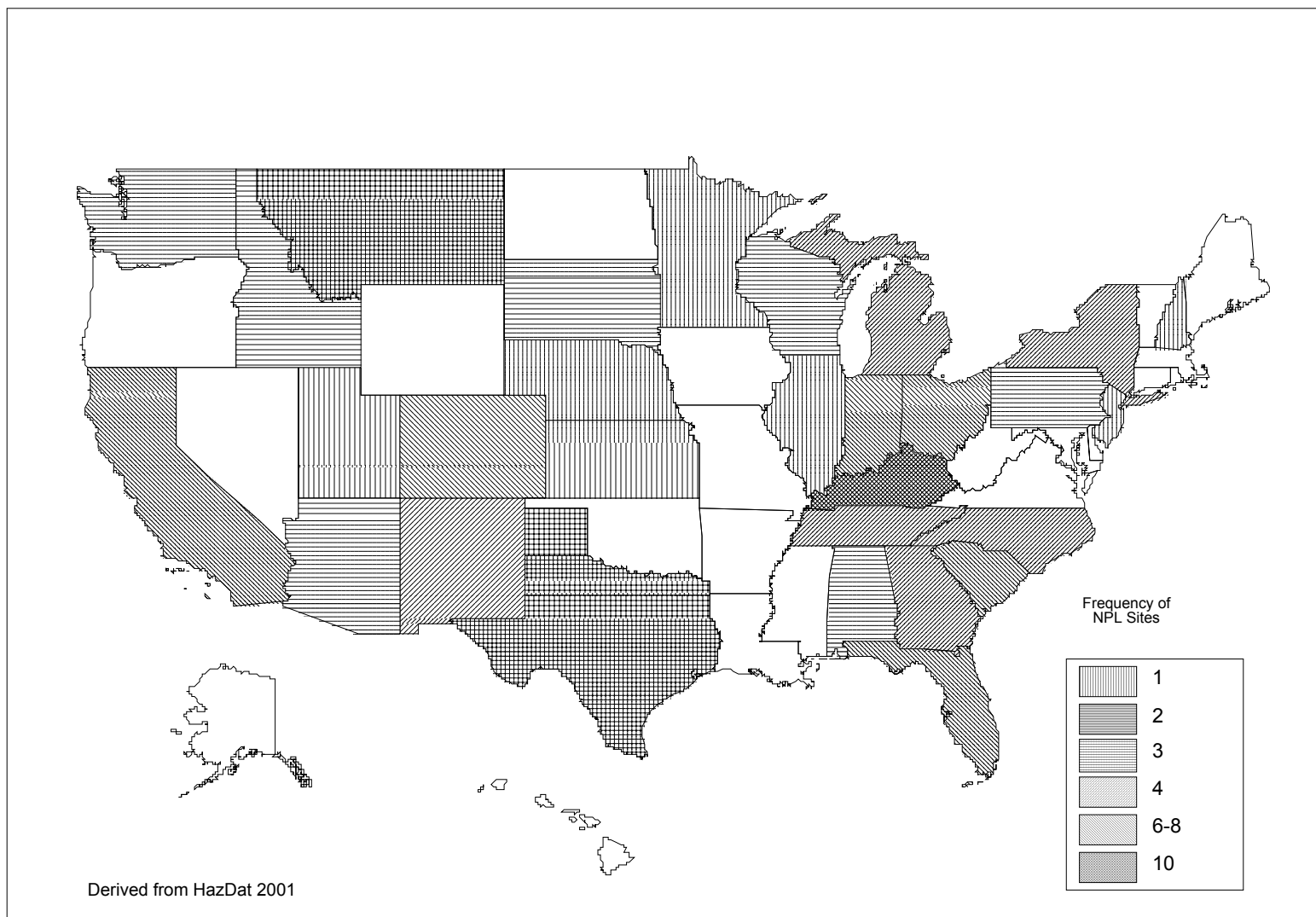
### 6.1 OVERVIEW

Strontium has been identified in at least 101 of the 1,585 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2001). However, the number of sites evaluated for strontium is not known. The frequency of these sites can be seen in Figure 6-1. Of these sites, 101 are located within the United States and none are located in the Commonwealth of Puerto Rico (not shown).

Strontium is widely distributed in the earth's crust and oceans. Strontium is released into the atmosphere primarily as a result of natural sources, such as entrainment of dust particles and resuspension of soil. Radioactive strontium is released into the environment as a direct result of anthropogenic activities. Stable strontium can be neither created nor destroyed. However, strontium compounds may transform into other chemical compounds. Radioactive strontium is formed by nuclear reactions. Radioactive decay is the only mechanism for decreasing the concentration of radiostrontium. The half-life of  $^{90}\text{Sr}$  is 29 years. Eventually, all of the radioactive strontium will be converted to stable zirconium (see Section 4.2).

Strontium present in the atmosphere is in the form of wet or dry aerosols. The principal chemical species in the air is strontium oxide. Strontium oxide can undergo transformation to strontium ions by reaction with water. Strontium is dispersed by atmospheric cycling and subsequently deposited by wet deposition on the earth's surface. In surface and groundwater, strontium exists primarily as a hydrated ion. Strontium can form ionic complexes with other inorganic or organic substances. Strontium is relatively mobile in water. However, the formation of insoluble complexes or sorption of strontium to soils can reduce its mobility in water. Strontium sorbs to soils by ion exchange; and tends to be more mobile in soils with a high concentration of exchangeable ions or in soils with low cation exchange capacities. Strontium is taken up and retained by aquatic and terrestrial plants and is concentrated in the boney tissues of animals that eat contaminated vegetation. The average concentration of strontium in urban air is  $20 \text{ ng/m}^3$  (Dzubay and Stevens 1975). The concentration of  $^{90}\text{Sr}$  in the atmosphere has steadily decreased since its maximum concentration in 1963. The mean concentration of strontium in U.S. surface water is  $<1 \text{ mg/L}$ . Dissolved strontium has been detected in groundwater and surface water used for drinking water supplies with average concentrations of 1.6 and 424 mg/L, respectively (EPA 2000c). The median concentration of  $^{90}\text{Sr}$  in drinking water for 1995 was  $0.1 \text{ pCi/L}$  ( $3.7 \text{ mBq/L}$ ). Human exposure to

Figure 6-1. Frequency of NPL Sites with Strontium Contamination



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strontium and radiostrontium can result from consumption of food, drinking water, or incidental ingestion of soil or dust contaminated with strontium. Food and drinking water are the largest sources of exposure to strontium and radiostrontium. Grain, leafy vegetables, and dairy products contribute the greatest percentage of dietary strontium and radiostrontium to humans.

## 6.2 RELEASES TO THE ENVIRONMENT

### 6.2.1 Air

Strontium naturally occurs in the earth's crust and is released into the atmosphere as a result of natural processes such as entrainment of dust particles, resuspension of soil by wind, and sea spray. Entrainment of soil and dust particles with significant concentrations of strontium would be most significant in areas with higher soil strontium concentrations. Coastal regions have higher concentrations of strontium due to sea spray (Capo et al. 1998). Human activities, including milling and processing of strontium compounds, burning of coal, land application of phosphate fertilizers, and using pyrotechnic devices, release strontium into the atmosphere (Lee and von Lehmden 1973; Ondov et al. 1989; Perry 1999; Que Hee et al. 1982; Raven and Loeppert 1997). The effect of these activities is illustrated by the deposition rates of strontium measured in peat cores of northern Indiana. Deposition has increased by a factor of 7 from 8.1 mg strontium/m<sup>2</sup>/year in presettlement times (1339–1656) to 57.0 mg strontium/m<sup>2</sup>/year between 1970 and 1973 (Cole et al. 1990).

Strontium discharged into the atmosphere from the operation of coal fired power plants depends on the strontium concentration in coal, the amount of coal burned, and the efficiency of fly ash recovery. Approximately 90% of coal mass is consumed during the combustion process, leaving 10% as a residual nonvolatile material (fly ash) containing 100–4,000 ppm Strontium (or mg/kg) (Furr et al. 1977). Atmospheric concentrations of strontium emitted from coal fired power plants have been found to range from 17 to 2,718 mg/m<sup>3</sup> in the western United States and are approximately 9,786 mg/m<sup>3</sup> in the eastern United States (Ondov et al. 1989; Que Hee et al. 1982). Phosphate fertilizers are known to contain between 20 and 4,000 µg strontium/g solid by weight (Lee and von Lehmden 1973; Raven and Loeppert 1997). Strontium can be released into the atmosphere in windblown soil to which phosphate fertilizers have been applied. Pyrotechnic displays release low levels of strontium on the order of 5 mg/m<sup>3</sup> in the immediate environment of the display (Perry 1999).

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Radioactive strontium (e.g.,  $^{90}\text{Sr}$ ) was released into the atmosphere from aboveground testing of nuclear weapons during the period of 1945–1980. Nuclear weapon testing injects radioactive material into the stratosphere, which results in wide dispersal of radionuclides. However, atmospheric deposition of  $^{90}\text{Sr}$  has steadily decreased from a high in 1963 of approximately  $1.10 \times 10^8$  GBq (3.0 MCi) to <3000 Ci in 1990, which suggests that global concentrations of  $^{90}\text{Sr}$  in the atmosphere have declined (DOE 1996c). Other sources of regional contamination from radiostrontium include large-scale nuclear power plant accidents such as the Chernobyl disaster in the Ukraine (April 1986) which resulted in releases of about 2.2 MCi ( $8.1 \times 10^7$  GBq) of  $^{89}\text{Sr}$  and 0.22 MCi ( $8.1 \times 10^6$  GBq) of  $^{90}\text{Sr}$  into the atmosphere (Eisenbud 1987). However, although some  $^{90}\text{Sr}$  reached the upper atmosphere and was subsequently transported around the world, most of the radiostrontium was deposited as regional fallout in eastern Europe (Eisenbud 1987). Routine releases of radiostrontium in 1993 from the operation of nuclear power plants around the United States are summarized in Table 6-1 (NRC 1993b). In 1993, releases of radiostrontium (i.e.,  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$ , and  $^{91}\text{Sr}$ ) for boiling water (BWR) and pressurized water (PWR) nuclear reactors (the two common designs of nuclear reactors in the United States) were 72.1 and 3.3 mCi (2.67 and 0.12 GBq), respectively. The total annual releases of radiostrontium from nuclear power plants in the United States (75.4 mCi or 2.79 GBq) are insignificant compared to releases of  $^{90}\text{Sr}$  from the testing of nuclear weapons. In the former Soviet Union between the years 1949–1956, large-scale environmental contamination occurred in the region surrounding the Mayak plutonium production complex in the Ural region of Russia (Eisenbud and Gesell 1997). Releases of radioactive liquid wastes into the Techa River, both planned and accidental, of about  $10^{17}$  Bq (2.7 MCi) resulted.  $^{90}\text{Sr}$  contributed about 12% (or 0.23 MCi) to the total activity released (Tokareva et al. 2000). Other minor releases of  $^{90}\text{Sr}$  have involved accidents with rockets or satellites that have disintegrated in the atmosphere. The Soviet satellite Cosmos 954 powered by a plutonium fueled nuclear reactor released  $3.1 \times 10^3$  GBq (83 Ci) of  $^{90}\text{Sr}$  to the regional atmosphere in northern Canada in 1978 (Eisenbud 1987). The Department of Energy (DOE) and its predecessor agencies have been involved in operations that have released radiostrontium into the atmosphere. Figure 6-2 maps the location of current DOE offices, facilities and laboratories across the United States. Over the 43-year operating period at the DOE Savannah River Site in South Carolina, about  $1.1 \times 10^2$  GBq (3 Ci) of  $^{90}\text{Sr}$  was released into the atmosphere, primarily from the chemical separation and reprocessing of nuclear fuel (Carlton et al. 1998, 1999). Between 1944 and 1972, about 64 Ci ( $2.4 \times 10^3$  GBq) of  $^{90}\text{Sr}$  and 700 Ci ( $2.6 \times 10^4$  GBq) of  $^{89}\text{Sr}$  was released into the atmosphere at the DOE Hanford site in Washington state from the routine operation of chemical plants used to separate plutonium from spent reactor fuel (CDC 1994).

**Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993**

Installation	Location <sup>a</sup>	Annual Total Site Environmental Releases for 1993						
		Water				Air		
		<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi	<sup>92</sup> Sr, mCi	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi
Boiling Water Reactors								
Browns Ferry <sup>b</sup>	Decatur, AL	41.1	2.05	—	0.40	0.19	—	—
Brunswick <sup>b</sup>	Wilmington, NC	—	—	—	0.0062	0.099	0.0027	—
Clinton	Clinton, IL	—	—	—	—	0.06	—	—
Cooper	Omaha, NE	4.69	15.8	—	0.082	—	—	—
Dresden <sup>b</sup>	Joliet, IL	0.056	0.085	—	—	0.67	0.004	—
Duane Arnold	Cedar Rapids, IA	—	—	—	—	0.018	0.0009	—
Edwin I. Hatch	Baxley, GA	6.29	0.43	5.20	0.65	12.0	0.24	—
Fermi	Laguna Beach, MI	0.19	—	—	—	0.14	0.0003	4.0
Grand Gulf	Vicksburg, MS	0.32	0.29	—	—	0.003	0.002	—
Hope Creek	Wilmington, DE	—	—	—	—	—	—	—
Humbolt Bay <sup>b</sup>	Eureka, CA	—	36.5	—	—	—	0.002	—
James A. Fitzpatrick	Syracuse, NY	0.44	—	—	—	0.045	7.3x10 <sup>-7</sup>	—
LaCrosse <sup>b</sup>	LaCross, WI	—	0.28	—	—	—	0.0003	—
LaSalle	Ottawa, IL	—	—	—	—	—	—	—
Limerick	Philadelphia, PA	20.0	0.44	—	—	16.4	0.31	—
Millstone	New London, CT	3.30	0.15	—	0.55	0.22	0.0006	—

Monticello St. Cloud, MN – – – – 0.59 0.003 –

**Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993 (continued)**

		Annual Total Site Environmental Releases for 1993						
Installation	Location <sup>a</sup>	Water				Air		
		<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi	<sup>92</sup> Sr, mCi	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi
Boiling Water Reactors (contd.)								
Nine Mile Point	Oswego, NY	<0.0001	—	—	—	5.90	0.004	—
Oyster Creek	Toms River, NJ	—	—	—	—	1.17	0.014	—
Peach Bottom	Lancaster, PA	0.19	0.056	—	—	4.9	0.021	3.76
Perry	Painesville, OH	0.22	0.008	—	—	1.8	0.009	4.87
Pilgram	Boston, MA	1.63	0.086	—	—	5.8	0.024	—
Quad-Cities	Moline, IL	0.050	0.018	—	0.12	0.61	0.0014	—
River Bend	Baton Rouge, LA	5.3	0.31	—	—	0.30	0.0095	—
Shoreham	Brookhaven, NY	0.025	—	—	—	—	—	—
Susquehanna	Berwick, PA	0.0088	—	—	0.0011	0.0003	—	—
Vermont Yankee	Brattleboro, VT	—	—	—	—	2.83	0.054	—
WNP-2	Richland, WA	0.55	0.057	—	—	3.5	0.012	1.61
Total		84.4	56.6	5.20	1.81	57.2	0.72	14.2
Pressurized Water Reactors								
Arkansas One	Russellville, AR	2.81	1.17	—	0.59	0.0008	—	—
Beaver Valley	Shippingport, PA	—	—	—	0.08	—	—	—

**Table 6-1. Radiostrontium Releases from Nuclear Power Plants for 1993 (continued)**

Installation	Location <sup>a</sup>	Annual Total Site Environmental Releases for 1993						
		Water				Air		
		<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi	<sup>92</sup> Sr, mCi	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi
Big Rock Point	Charlevoix, MI	0.02	0.17	–	–	0.21	0.006	2.73
Pressurized Water Reactors (contd.)								
Braidwood	Joliet, IL	3.68	158.4	–	0.017	–	–	–
Byron	Byron, IL	152.4	0.56	–	–	–	–	–
Callaway	Fulton, MO	17.6	1.12	–	–	0.004	–	–
Calvert Cliffs	Washington, DC	0.83	0.37	–	–	–	–	–
Catawaba	Rock Hill, SC	–	–	–	0.41	–	–	–
Comanche Peak	Glen Rose, TX	–	–	–	0.029	–	–	–
Crystal River	Tampa, FL	3.03	10.2	–	3.57	0.001	0.001	–
Davis-Besse	Toledo, OH	–	–	–	–	–	–	–
Diablo Canyon	San Luis Obispo, CA	0.16	0.057	–	0.003	–	–	–
Donald C. Cook	St. Joseph, MI	–	0.029	–	–	0.080	0.0005	–
Fort Calhoun	Omaha, NE	0.61	0.77	–	–	–	0.0007	–
H.B. Robinson	Hartsville, SC	–	–	–	–	–	–	–
Haddam Neck	Middletown, CT	0.076	1.52	–	–	0.0002	0.0002	–
Harris <sup>b</sup>	Raleigh, NC	–	–	–	–	–	–	–
Indian Point <sup>b</sup>	Peekskill, NY	0.077	0.007	–	–	–	–	–

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		Water				Air		
Installation	Location <sup>a</sup>	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi	<sup>92</sup> Sr, mCi	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi
Pressurized Water Reactors (contd.)								
Joseph M. Farley	Dothan, AL	—	0.028	—	0.10	—	—	—
Kewaunee	Green Bay, WI	0.92	0.051	—	—	—	—	—
Maine Yankee	Wicasset, ME	0.15	—	—	—	—	—	—
McGuire	Charlotte, NC	0.20	—	—	—	—	—	—
North Anna <sup>c</sup>	NW Richmond, VA	—	—	—	—	—	—	—
Oconee	Greenville, SC	—	—	—	—	—	—	—
Palisades	South Haven, MI	0.003	0.012	—	—	0.011	0.0042	—
Palo Verde	Phoenix, AZ	—	—	—	—	0.19	0.0009	—
Point Beach	Manitowoc, WI	0.012	0.11	0.0052	—	—	0.0001	—
Prairie Island	Minneapolis, MN	—	—	—	0.029	0.0006	0.0003	—
R.E. Ginna	Rochester, NY	0.30	0.090	—	—	—	—	—
Rancho Seco <sup>b</sup>	Sacramento, CA	—	0.0013	—	—	—	—	—
San Onofre <sup>b</sup>	San Clemente, CA	4.26	0.36	—	0.48	—	—	—
Seabrook	Portsmouth, NH	—	—	—	—	—	—	—
Sequoyah	Daisy, TN	0.35	0.29	0.023	0.54	—	—	—
South Texas	Bay City, TX	—	—	—	—	—	—	—



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		Water				Air		
Installation	Location <sup>a</sup>	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi	<sup>92</sup> Sr, mCi	<sup>89</sup> Sr, mCi	<sup>90</sup> Sr, mCi	<sup>91</sup> Sr, mCi
Pressurized Water Reactors (contd.)								
St. Lucie	Ft. Pierce, FL	1.21	1.83	—	—	—	0.0012	—
Summer	Columbia, SC	0.0007	0.021	—	—	—	—	—
Surry	Newport News, VA	—	—	—	—	—	—	—
Three Mile Island <sup>b</sup>	Harrisburg, PA	0.034	0.83	—	—	—	0.0003	—
Trojan <sup>b</sup>	Portland, OR	0.24	0.029	—	—	—	—	—
Turkey Point <sup>b</sup>	Florida City, FL	12.7	3.55	—	—	—	—	—
Vogtle	Augusta, GA	1.64	0.19	—	—	0.0025	0.0003	—
Waterford	New Orleans, LA	—	—	—	0.23	—	—	—
Wolf Creek	Burlington, KS	—	0.092	0.0087	—	—	—	—
Yankee Rowe <sup>b</sup>	Greenfield, MA	—	—	—	—	—	—	—
Zion	Waukegan, IL	—	—	—	5.93	—	—	—
Total		207.1	182.8	0.04	11.5	0.50	0.02	2.73

Source: NRC 1993b

<sup>a</sup>Post office state abbreviations used<sup>b</sup>Facilities that are permanently or indefinitely shut down<sup>c</sup>air <sup>85</sup>Sr 8.17x10<sup>6</sup>

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**Figure 6-2. Major DOE Offices, Facilities, and Laboratories\***Operations Offices (O)

Oakland, CA  
 Idaho Falls, ID  
 Chicago, IL  
 Las Vegas, NV  
 Albuquerque, NM  
 Savannah, SC  
 Oak Ridge, TN  
 Richland, WA

Laboratories/National Laboratories (\*)

Lawrence Berkeley Nat. Lab. (CA)  
 Lawrence Livermore Nat. Lab. (CA)  
 Stanford Linear Accelerator (CA)  
 Nat. Renewable Energy Lab. (Golden CO)  
 Idaho Nat. Energy & Env. Lab. (ID)  
 Fermi Nat. Accelerator Lab. (Batavia, IL)  
 Argonne Nat. Lab. (IL)  
 Ames Lab (IA)  
 MIT Bates Lab (MA)  
 Princeton Plasma Physics Lab (NJ)  
 Inhalation Toxicology Res. Inst. (Albuquerque, NM)  
 Sandia Nat. Labs. (Albuquerque NM)  
 Brookhaven Nat. Lab (NY)  
 Oak Ridge Nat. Lab. (TN)  
 T Jefferson Nat. Accelerator (Newport News VA)  
 Pacific Northwest Nat. Lab. (Richland, WA)

Special Purpose Offices (X)

Energy Technology Eng. Center (Los Angeles CA)  
 Naval Petroleum. Reserves 1 & 2 (Kern, CA)  
 Naval Oil Shale Reserves 1 & 3 (Rifle, CO)  
 Strategic Petroleum Reserve (LA)  
 Yucca Mountain Project (NV)  
 Nat. Petroleum . Tech. Office (Tulsa, OK)  
 Federal Energy Tech. Centers (PA, WV)  
 Oak Ridge Inst. for Science & Education (TN)  
 Naval Oil Shale Reserves 2 (Vernal, UT)  
 Naval Petroleum Reserve 3 (Casper, WY)

Field Offices (#)

Rocky Flats, CO  
 Golden, CO  
 Ohio (4 sites in Ohio)

Facilities (+)

Grand Junction, CO  
 Rocky Flats, CO  
 Pinellas, FL  
 Idaho Falls, ID  
 Kansas City Plant (MO)  
 Nevada Test Site (NV)  
 Waste Isolation Plant (Carlsbad, NM)  
 Fernald Env. Management Project (OH)  
 Mound Env. Management Project (OH)  
 Savannah River (SC)  
 Oak Ridge Reservation (TN)  
 Pantex Plant (Amarillo, TX)  
 Hanford, WA

\* Post office state abbreviations used

Source: DOE 2000 <http://www.doe.gov/people.htm>

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**6.2.2 Water**

Releases of strontium to surface water and groundwater results from the natural weathering of rocks and soils and by the discharge of waste water directly into streams and aquifers. Intentional and unintentional releases of radioactive strontium directly into streams have occurred at DOE sites across the country. Over the period of 1954–1989, about 104 Ci ( $3.8 \times 10^3$  GBq) of  $^{90}\text{Sr}$  and 216 Ci ( $8.0 \times 10^3$  GBq) of  $^{89}\text{Sr}$  were released to streams in the vicinity of the Savannah River Site (Carlton et al. 1998; Cummins et al. 1991). During the period from 1952 to 1991, >129 Ci of  $^{90}\text{Sr}$  in waste water was discharged into pits, wells, and infiltration ponds at the Idaho Chemical Processing Plant in Idaho, some of which may find its way into surface or groundwater (Bartholomay et al. 1995). Minor releases of radioactive strontium to water occur annually from nuclear power plants. Table 6-1 summarizes the releases of radioactive strontium from nuclear power plants into surface waters in 1993 (NRC 1993b). Releases of radiostrontium (i.e.,  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$ ,  $^{91}\text{Sr}$ , and  $^{92}\text{Sr}$ ) into surface waters in 1993 from BWR and PWR were 146.2 mCi (5.41 GBq) and 401.4 mCi (14.9 GBq), respectively.

**6.2.3 Soil and Sediments**

Strontium is ubiquitous in the environment and is present in nearly all rocks and soils. It is released to land in solid waste and from the use of phosphate fertilizers.  $^{90}\text{Sr}$  is found in nearly all soils in the United States.  $^{90}\text{Sr}$  that is deposited at a specific site varies widely, depending primarily on rainfall. Intentional and unintentional releases of radioactive strontium have occurred at DOE sites across the country. Between 1954 and 1989 at the Savannah River Site, 105 Ci ( $3.9 \times 10^3$  GBq) of  $^{89}\text{Sr}$  and 299 Ci ( $1.1 \times 10^4$  GBq) of  $^{90}\text{Sr}$  were released into seepage basins on site (DOE 1991). About 100 million gallons of liquid HLW are stored in underground tanks in Hanford, Washington, Savannah River, South Carolina, Idaho National Engineering Laboratory, Idaho, and West Valley, New York; these tanks contain a variety of radioactive liquids, solids, and sludges with unknown characteristics. Sixty-seven tanks at the Hanford site have suspected leaks of HLW into the surrounding soil. The largest three confirmed leaks at the Hanford site have released 115,000, 70,000, and 55,000 gallons of HLW, respectively, which may contain  $^{90}\text{Sr}$  as well as other radionuclides (DOE 1996a).

## 6.3 ENVIRONMENTAL FATE

### 6.3.1 Transport and Partitioning

Strontium, present in crustal materials, is released by the weathering force of wind and water. Strontium leaves the oceans, the largest reservoir of dissolved strontium, by deposition in marine carbonate sediment. Some strontium is transported from oceans to the atmosphere in sea spray, returning to the terrestrial environment in the form of precipitation (Capo et al. 1998).

Strontium released into the atmosphere from natural and anthropogenic activities is transported and redeposited on the earth by dry or wet deposition. Dry deposition results from gravitational settling, impact, and sorption on surfaces (NCRP 1984). Experimental data on dry deposition of strontium, present in the ambient atmosphere, is limited. Rain, sleet, snow, or other forms of moisture can wash airborne particles containing strontium from the atmosphere by the process of wet deposition. Wet deposition depends on conditions such as particle solubility, air concentration, rain drop size distribution, and rain fall rate (NCRP 1984). Hirose et al. (1993) examined the mechanism of aerial deposition of  $^{90}\text{Sr}$  derived from the Chernobyl accident, and found that 96% of atmospheric  $^{90}\text{Sr}$  returned to earth as wet deposition.

Like calcium, strontium has moderate mobility in soils and sediments, and sorbs moderately to metal oxides and clays (Hayes and Traina 1998). The  $\text{Sr}^{2+}$  ion is strongly hydrated and is firmly coordinated with six or more water molecules in aqueous solution. When  $\text{Sr}^{2+}$  ions sorb on negatively charged mineral surface sites, the hydration sphere is retained (O'Day et al. 2000). Strontium sorbs as hydrated ions on the surface of clay minerals (kaolinite), weathered minerals (amorphous silica), and iron oxides (Sahai et al. 2000). Sorbed carbonate on iron oxides enhances the sorption of  $\text{Sr}^{2+}$  and permits the nucleation of  $\text{Sr}^{2+}$  as strontium carbonate (Sahai et al. 2000). On calcite (calcium carbonate),  $\text{Sr}^{2+}$  sorption occurs by electrostatic attraction as hydrated ions. However, at higher concentrations, precipitation of strontianite (strontium carbonate) occurs and strontium is likely to be less mobile (Parkman et al. 1998).

A wide variation of  $K_d$  values have been published in the literature for  $\text{Sr}^{2+}$  sorption (NCRP 1984) that reflect differences in soil and sediment conditions as well as the analytical techniques used (Bunde et al. 1997).  $K_d$  values of 15–40 L/kg were measured for  $^{90}\text{Sr}^{2+}$  in aquifer sediments near Liquid Waste Disposal Facilities at the Hanford site in Washington, where rapid ion exchange dominates (DOE 1996d).  $K_d$  was measured for  $^{90}\text{Sr}^{2+}$  in aquifer sediments beneath waste water ponds that contained high salt

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concentrations at the Idaho National Environmental and Engineering Laboratory (INEEL) (Bunde et al. 1998); and values ranged from 56 to 62 L/kg at initial concentrations of sodium and potassium of 300 and 150 mg/L, respectively. For initial aqueous concentrations of sodium between 1,000 and 5,000 mg/L,  $K_d$  values were 4.7 and 19 L/kg, respectively. At the Chalk River Nuclear Laboratory in Ontario, Canada, a  $^{90}\text{Sr}$  waste plume in groundwater initially advanced rapidly as  $^{90}\text{Sr}$  was out competed by high concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  for sorption sites in sediments, and as concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  declined, the migration of the  $^{90}\text{Sr}$  plume slowed (Toran 1994). High salt concentrations (marine, brines, or high salinity water) can increase the mobility of  $^{90}\text{Sr}^{2+}$  by decreasing strontium sorption to sediments (Bunde et al. 1997, 1998) and increase the transport of strontium with the environmental cycling of water. Organic matter in soils has a substantial effect on the transport of strontium through soils into groundwater.  $K_d$  values decreased down the soil profile in Podzol forest soil with an organic rich top soil and lower clay layers, from 140 to 44 L/kg, respectively (Bunzl and Schimmack 1989).  $\text{Sr}^{2+}$  chemically complexes with organic matter by partially neutralizing exchangeable sites on organic matter resulting in the precipitation of organic matter- $\text{Sr}^{2+}$  complexes (Helal et al. 1998a). High concentrations of ion exchangeable  $\text{Ca}^{2+}$  in soil enhances the complexation of  $\text{Sr}^{2+}$  with organic matter, and increases the removal of  $\text{Sr}^{2+}$  from solution which results in reduced  $\text{Sr}^{2+}$  mobility (Helal et al. 1998a). However, nitrate fertilizers inhibit the formation of  $\text{Sr}^{2+}$ -organic matter complexes and increase  $\text{Sr}^{2+}$  mobility (Helal et al. 1998b).

Strontium is not necessary for growth or reproduction for most plants, but is typically absorbed to satisfy the plant's metabolic requirements for calcium (NCRP 1984). Soil to plant concentration ratios for strontium (the ratio of the concentration of strontium in wet vegetation to the concentration of strontium in dry soil) are 0.017–1.0 (NCRP 1984), and indicate that strontium can be easily absorbed into plants from soil. The uptake of strontium by plants is greatest in sandy soils having low clay and organic matter content (Baes et al. 1986). The concentration of nutritive mineral elements in soil such as calcium lower the intake of strontium to the above ground phytomass. The average reduction of the soil-to-plant concentration ratios for  $^{90}\text{Sr}$  caused by amendment with Ca or K is around 50–60% (Lembrechts 1993).

Strontium may be deposited on plant surfaces from the atmosphere, remain on the plant, be washed off, or be absorbed directly into the plant through leaves. Contamination by direct deposition on foliage surfaces is predominantly a short term mechanism with a weathering half-life of approximately 14 days (Lassey 1979). Carini et al. (1999) examined the mechanism of translocation in three species of fruit-bearing plants exposed to aerial deposition of  $^{85}\text{Sr}$ ; and found that translocation of  $^{85}\text{Sr}$  is localized to the area of contamination on the plant. However, uptake of strontium through the leaves is minor compared to root

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uptake. Once absorbed in the plant, strontium translocates to other parts of the plant, such as the leaves or fruit. Translocation of strontium in plants is affected by the particular species and stage of organism growth, and the most metabolically active parts (growing) will accumulate higher concentrations of strontium (Kodaira et al. 1973).

Strontium, taken up by plants and translocated to the above ground plant compartments, has been observed for deep-rooted plants such as chasima (*Chrysothamnus nauseosus*), mulberry vegetation (*Morus alba*), quaking aspen (*Populus tremuloides*) and red maple (*Acer rubrum*) growing on top of low level waste burial sites or contaminated soils (Cooper and Rahman 1994; DOE 1995; Fresquez et al. 1996a). The top growth of the plant material releases strontium to the soil surface through leaf fall. Downward migration of  $^{90}\text{Sr}$  is slowed by recycling of the contaminated litter by vegetation (Cooper and Rahman 1994). Sub-surface  $^{90}\text{Sr}$  can be transported from soil to top soil by burrowing animals, and is spread to the surrounding environment via animal tissues and fecal deposits. At the Subsurface Disposal Area at the INEL, deer mice had the highest contamination of all animals from ingestion of  $^{90}\text{Sr}$ -contaminated low level nuclear waste. In addition, the biotic intrusion of soils covering the waste site brings water infiltration into buried LLW (Arthur and Janke 1986).

The uptake or bioaccumulation of strontium by plants and organisms is the mechanism by which strontium in air, water, and soil enters into the food chain of humans. Bioconcentration factors (BCFs) have been measured by several investigators in both aquatic and terrestrial organisms for  $^{90}\text{Sr}$  (NCRP 1984). BCF values for  $^{90}\text{Sr}$  in aquatic, terrestrial, and wetland ecosystems at the Savannah River Site were reported by Friday (1996) and are summarized in Table 6-2. The study illustrates that the organisms with the highest uptake are aquatic organisms such as fish (large-mouthed bass), macroinvertebrates (insects), macrophytes (white-water lilies and bladderwort), and zooplankton. Because of the similarity of strontium to calcium, boney fish had a very high BCF, with a value  $>50,000$  measured in the boney tissue (Friday 1996). In the muscle tissue of boney fish, BCF values for  $^{90}\text{Sr}$  ranged from high (benthic invertebrate and fish feeders; 610) to very high (piscivores; 3,400). Because strontium and calcium are chemically similar, the concentration of calcium in water can influence the bioaccumulation of strontium in biota. Organisms such as fish bioaccumulate strontium with an inverse correlation to levels of calcium in water. However, this correlation is not universal and does not apply to other organisms such as algae and plants (NCRP 1984).

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**Table 6-2. Selected Bioconcentration Factors for  $^{90}\text{Sr}$  in Aquatic, Wetland, and Terrestrial Ecosystems at the Savannah River Site**

Organism	Minimum	Bioconcentration factors for $^{90}\text{Sr}$	
		Maximum	Mean
Algae		600	
Clam, shell		1,300	
Fish muscle			
Insect and bottom invertebrate feeders		<48	
Piscivores		3,400	
Benthic invertebrate and fish feeders		610	
Fish bone			
Insect and bottom invertebrate feeders		2,400	
Piscivores		63,000	
Benthic invertebrate and fish feeders		57,000	
Detritus and plankton feeders		51,000	
Macroinvertebrates, larvae	520	54,000	27,300
Macrohytes (rooted vascular)	2,100	8,500	5,500
Macrophytes (floating vascular)		9,400	
Zooplankton		3,900	
Corn			
Grain		0.15	
Leaves		13.1	
Pine tree, leaves	0.88	1.69	1.29
Soybeans		2.51	
Tree (maple, sweetgum, and poplar)			
Wood		0.81	
Bark		11	
Leaf		3.8	

Source: Friday 1996

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**6.3.2 Transformation and Degradation**

Because strontium is an element, its atoms do not degrade by environmental processes such as hydrolysis or biodegradation. However, radioactive strontium will be subject to radioactive decay and transformation to other elements. Eventually, all of the radioactive strontium will be transformed into stable zirconium by the process of radioactive decay (see Section 4.2):



Both radioactive and nonradioactive strontium compounds are subject to both biotic and abiotic transformation mechanisms.

**6.3.2.1 Air**

The presence of strontium and radioactive strontium compounds in the atmosphere results from both natural and anthropogenic activities (see Section 6.2.1). Strontium is emitted into the atmosphere as strontium oxide (i.e., SrO) from emission during thermal processes. As is the case of other metallic compounds, SrO cannot be destroyed; however, it can be transformed from one form to another. When SrO comes in contact with water in clouds or during washout by rain, it ionizes to form  $\text{Sr}^{2+}$ . There is no evidence for interaction of SrO with  $\text{CO}_2$  (g) or other compounds in the atmosphere.

**6.3.2.2 Water**

Strontium exists almost exclusively in the environment as a +2 cation, and will form different species, some of which are more soluble than others. Because the different species have different solubilities, they will have different mobilities in the environment and different exposure potentials. Strontium exists either a hydrated cation, an ionic solution complex, or an ionic salt. In the environment, typical solution species for strontium are  $\text{Sr}^{2+}$  and  $\text{SrOH}^+$ , and some strontium compounds ( $\text{SrCO}_3$  and  $\text{SrSO}_4$ ) are practically insoluble in neutral water (Cotton and Wilkenson 1980; see Table 4-2).



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**6.3.2.3 Soils and Sediments**

The principal abiotic processes that transform strontium in soils and sediments are mediated by sorption and desorption reactions between the soil solution and matrix (precipitation, complexation, and ion exchange), and controlled by pH, ionic strength, solution speciation, mineral composition, organic matter, biological organisms, and temperature (see Section 6.3.1).

**6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT**

Strontium is widely distributed throughout the earth and has continuously cycled between the atmosphere, biosphere, hydrosphere, and lithosphere for many millions of years. Table 6-3 illustrates the average or range of concentrations of strontium in earth materials (Capo et al. 1998). Anthropogenic activities have increased local concentrations of strontium as a consequence of the development of an industrialized human society. Before the 1940s, radioactive strontium was not present in the environment at any measurable levels.

In the United States, commercial nuclear power plant operators are required to monitor and report any detectable quantities of radioactive materials released to the environment (NRC 1996). Table 6-1 summarizes releases of radiostrontium isotopes with half-lives >8 hours to the atmosphere and water for 1993 from PWR and BWR nuclear power plants. Nearly all of the radioactive material reported as released in effluents are from planned releases from normal plant operation or anticipated operational occurrences. The latter includes unplanned releases of radioactive materials from miscellaneous actions such as equipment failure, operator error, or procedure error, and are not of such consequence as to be considered an accident (NRC 1993b).

**6.4.1 Air**

According to two surveys, the strontium content in urban air ranges from 4 to 100 ng/m<sup>3</sup> and averages 20 ng/m<sup>3</sup> (Dzubay and Stevens 1975). The arithmetic mean concentration of strontium in urban air was measured as 29.1 ng/m<sup>3</sup> in the Los Angeles basin during 1985 (Witz et al. 1986). Urban air in Illinois between 1985 and 1988 averaged 0.9–4.8 ng/m<sup>3</sup> (Sweet et al. 1993). Areas where higher strontium concentrations are prevalent are near coal burning plants where strontium can be released with stack emissions as discussed in Section 6.2.1.

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**Table 6-3. Average or Ranges of Concentration of Strontium in Earth Materials**

Material	Concentration of Strontium
Geologic (ppm)	
Average crust	370
Exposed upper crust	337
Soil:	
Soil minerals	240
Soil (labile)	0.2–20
Individual rock types:	
Basalt	465
Carbonate	610
High-Ca granite	440
Low-Ca granite	100
Sandstone	20
Shale	300
Biologic (ppm)	8–2,500
Wood	19
Roots (spruce)	19
Conifer needles	2–20
Hydrologic (µg/L)	
Seawater	7.620
Rivers	6–800
Rain	0.7–383
Snow	0.01–0.76

Source: Capo et al. 1998

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Before the 1940s, radiostrontium was not present in the air at any significant concentrations. Concentrations of  $^{90}\text{Sr}$  in the atmosphere peaked at about 10 MCi (0.37 GBq) in 1963 coincident with the period of extensive atmospheric nuclear weapons testing. Since the signing of the Nuclear Test Ban Treaty of 1963, the concentration of  $^{90}\text{Sr}$  has steadily dropped through the latter 35 years by deposition and radioactive decay (DOE 1996c; Eisenbud 1987). Recent levels of  $^{90}\text{Sr}$  in air were not located.

### 6.4.2 Water

Surveys of strontium in surface waters and municipal water supplies across the United States show that strontium is present in nearly all fresh waters in amounts  $<1$  mg/L (USGS 1963). The average concentration of strontium in streams of the United States is between 0.5 mg/L and 1.5 mg/L. Strontium concentrations  $>1$  mg/L are found in streams of the southwest, where the total dissolved solids content is the highest of any area of the continental United States. Streams of most of the Atlantic slope basins, southern United States, upper Great Lakes region, and Pacific northwest contain concentrations of strontium that are generally  $<0.5$  mg/L Strontium (USGS 1963). Some exceptions are areas where there are celestite rich limestone deposits, such as regions of northwestern Ohio and eastern Florida (USGS 1963). The average concentration of strontium in sea water is approximately 8 mg/L (Demayo 1986). In groundwater, the average concentration of strontium is  $<0.5$  mg/L. High concentrations of strontium,  $>1$  mg/L, have been observed in the southwestern United States. Unusually high concentrations of strontium,  $>20$  mg/L, have been observed for some wells in central Wisconsin (USGS 1963). The National Drinking Water Contaminant Occurrence Database (NDOD), which contains data from ambient water samples, lists the number of detections of strontium in groundwater and surface water at several locations around the United States. Dissolved strontium was detected in groundwater at 4,593 of 4,614 sites (99.5% of sites), with a median and average concentrations of 0.38 and 1.6 mg/L, respectively. In surface water, dissolved strontium was detected at 1,829 of 1,836 sites (99.6% of sites), with median and average concentrations of 160 and 424 mg/L, respectively (EPA 2000c). The concentration of dissolved strontium in publicly owned treatment works (POTW) influents was between 0.025 and 0.45 mg/L (EPA 1981). The average concentrations of strontium in rain and snow were 0.7–383 and 0.01–0.76 mg/L, respectively (Capo et al. 1998).

$^{90}\text{Sr}$  concentration in surface waters of the north Pacific Ocean has decreased steadily since the early 1960s to present day levels of approximately 23–81 pCi/m<sup>3</sup> (1–3 Bq  $^{90}\text{Sr}$ /m<sup>3</sup>) sea water. This value is estimated by dividing the concentration levels for  $^{137}\text{Cs}$  by the global fallout activity ratio measured for

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$^{137}\text{Cs}/^{90}\text{Sr}$  of 1.5 (Hamilton et al. 1996). The EPA ERAMS program monitors ambient concentrations of  $^{90}\text{Sr}$  in drinking water at 78 sites. ERAMS data serve to assess trends and anomalies in concentrations, and to compare with standards set forth in the EPA National Interim Primary Drinking Water Regulations. Table 6-4 summarizes drinking water composite samples for the period of January–December in 1995 taken at the 78 sites in major population centers or near selected nuclear facilities (EPA 2000a). The median concentration of  $^{90}\text{Sr}$  in drinking water for this period was 0.1 pCi/L (4 mBq). Sites with above average levels of  $^{90}\text{Sr}$ , Detroit and Niagara Falls, recorded levels of 0.4 and 0.5 pCi/L (~15 mBq/L), respectively. In a 1974 study, a concentration of 0.09 pCi/L  $^{90}\text{Sr}$  (3 mBq/L) in drinking water was measured in Los Angeles, California (Kraybill 1983). In a survey that examined 169 wells used for public drinking water in California (Storm 1994), 16 wells measured recordable concentrations of  $^{90}\text{Sr}$ , with an average concentration of 105 pCi/L (4 Bq/L). NDOD lists the number of detections of  $^{90}\text{Sr}$  in groundwater and surface water at several locations around the United States. Dissolved  $^{90}\text{Sr}$  was detected in groundwater at 19 out of 101 sites, with median and average concentrations of 1.9 and 1.38 nCi/L (70 and 51 Bq), respectively. Dissolved  $^{90}\text{Sr}$  was detected in surface waters at one out of nine sites (11.1% of sites), with an average concentration of 0.5 pCi/L (19 mBq/L) (EPA 2000c). The concentrations of  $^{90}\text{Sr}$  in groundwater at the 91 waste sites located at 18 DOE facilities were between 0.05 and 231,000 pCi/L (2 mBq and 9 kBq) (DOE 1992). The DOE Environmental Measurements Laboratory program measures the  $^{90}\text{Sr}$  content of wet deposition in selected sites across the world to determine global trends in  $^{90}\text{Sr}$  deposition. The data for the year 1990 are presented in Table 6-5 for cities in the United States. The average total annual wet deposition of  $^{90}\text{Sr}$  in the United States was 5 pCi/m<sup>2</sup> (0.2 Bq/m<sup>2</sup>) during this period. The precipitation samples with the highest total  $^{90}\text{Sr}$  concentrations were obtained from New York City and Nome, Alaska with annual totals of 10 and 8 pCi/m<sup>2</sup> (0.4 and 0.3 Bq/m<sup>2</sup>), respectively. In all cases, the  $^{90}\text{Sr}$  concentrations in rain were low, which suggests that the atmospheric content of  $^{90}\text{Sr}$  in 1990 was small and decreasing (DOE 1996c).

### 6.4.3 Soils and sediments

Table 6-3 summarizes the average or range of concentrations of strontium in soils, sediment, and bedrock minerals. The average concentrations of strontium in the earth's crust and the exposed upper crust are 370 and 337 mg/kg, respectively. Soils on average have approximately 240 mg/kg Sr (Capo et al. 1998; EPA 1995). Some materials, such as soil amendments, are routinely applied to agricultural lands. Typical concentrations of strontium in soil amendments are: POTW sewage sludges, 250±192 ppm (mg/kg dry weight); phosphate fertilizers, 610 mg/kg; limestone, 610 mg/kg; and manure, 80 mg/kg dry weight (EPA 1995; Mumma et al. 1984).

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**Table 6-4.  $^{90}\text{Sr}$  in Drinking Water (Composites) for January–December 1995<sup>a</sup>**

State	City	Total solids (mg/L)	$^{90}\text{Sr}$	
			pCi/L	$\pm 2\sigma$
AK	Fairbanks	162.0	0.0	0.2
AL	Dothan	160.0	0.1	0.1
AL	Montgomery	55.2	0.1	0.2
AL	Muscle Shoals	82.0	0.2	0.2
AL	Scottsboro	87.0	0.2	0.2
AR	Little Rock	28.8	0.0	0.2
CA	Berkeley	8.0	0.1	0.2
CA	Los Angeles	318.0	0.0	0.1
CO	Denver	140.0	0.0	0.2
CO	Platteville	138.0	0.0	0.2
CT	Hartford	36.6	0.3	0.2
DE	Dover	191.0	ND	–
FL	Miami	150.0	0.2	0.2
FL	Tampa	252.0	0.3	0.2
GA	Baxley	165.0	0.0	0.2
GA	Savannah	147.0	ND	–
HI	Honolulu	208.0	0.1	0.1
IA	Cedar Rapids	121.0	0.1	0.2
ID	Boise	95.5	ND	–
ID	Idaho Falls	219.0	ND	–
IL	Morris	474.0	ND	–
IL	West Chicago	337.0	0.1	0.1
KS	Topeka	364.0	0.2	0.2
LA	New Orleans	226.0	0.2	0.2
MA	Lawrence	93.8	0.2	0.2
MD	Baltimore	89.8	0.1	0.2
MD	Conowingo	155.0	0.1	0.2
ME	Augusta	85.2	0.3	0.2
MI	Detroit	79.8	0.4	0.2

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**Table 6-4.  $^{90}\text{Sr}$  in Drinking Water (Composites) for January–December 1995<sup>a</sup> (continued)**

State	City	Total solids (mg/L)	$^{90}\text{Sr}$	
			pCi/L	$\pm 2\sigma$
MI	Grand Rapids	125.0	0.3	0.2
MN	Minneapolis	93.8	0.3	0.2
MN	Red Wing	238.0	0.0	0.2
MO	Jefferson City	283.0	0.0	0.2
MS	Jackson	86.8	0.2	0.2
MS	Port Gibson	313.0	0.0	0.1
MT	Helena	61.8	0.1	0.2
NC	Charlotte	46.8	0.1	0.2
NC	Wilmington	110.0	0.2	0.2
ND	Bismarck	329.0	0.0	0.2
NE	Lincoln	305.0	0.1	0.2
NH	Concord	81.2	0.1	0.2
NJ	Trenton	92.7	0.1	0.2
NJ	Waretown	52.0	0.0	0.2
NM	Santa Fe	279.0	ND	–
NV	Las Vegas	248.0	0.1	0.2
NY	Albany	68.8	0.3	0.2
NY	New York City	44.5	0.0	0.2
NY	Niagara Falls	99.2	0.5	0.2
NY	Syracuse	94.8	0.3	0.2
OH	Cincinnati	198.0	0.2	0.2
OH	Columbus	362.0	0.0	0.3
OH	East Liverpool	215.0	0.3	0.2
OH	Painesville	126.0	0.2	0.3
OH	Toledo	148.0	0.3	0.3
OK	Oklahoma City	62.6	0.3	0.2
OR	Portland	19.2	0.1	0.2
PA	Columbia	121.0	0.1	0.2
PA	Harrisburg	51.2	0.1	0.2

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**Table 6-4. <sup>90</sup>Sr in Drinking Water (Composites) for January–December 1995<sup>a</sup> (continued)**

State	City	Total solids (mg/L)	<sup>90</sup> Sr	
			pCi/L	±2σ
PA	Philadelphia	165.0	0.0	0.2
PA	Philadelphia-Queen	207.0	0.1	0.2
PA	Philadelphia-Baxter	101.0	0.2	0.2
PA	Pittsburgh	178.0	0.2	0.2
PC	Corozal	71.6	0.1	0.2
RI	Providence	52.8	0.3	0.2
SC	Barnwell	73.6	0.0	0.2
SC	Columbia	28.2	0.0	0.2
SC	Jenkinsville	165.0	ND	–
SC	Seneca	35.2	0.1	0.2
TN	Chattanooga	82.2	0.2	0.2
TN	Knoxville	93.8	0.0	0.2
TX	Austin	180.0	0.0	0.2
VA	Doswell	193.0	0.0	0.2
VA	Lynchburg	45.2	0.1	0.2
VA	Virginia Beach	91.2	0.3	0.2
WA	Richland	77.2	0.1	0.2
WA	Seattle	29.8	0.0	0.2
WI	Genoa City	194.0	ND	–
WI	Madison	234.0	ND	–

<sup>a</sup>Source: EPA 1995

Post office state abbreviations used

ND = Not detected

**Table 6-5. Quarterly and Annual Deposition of <sup>90</sup>Sr in Selected U.S. Cities for the Year 1990**

Location	Quarter								Annual Total	
	First		Second		Third		Fourth			
	<sup>90</sup> Sr Deposition	Precipitation	<sup>90</sup> Sr Deposition	Precipitation	<sup>90</sup> Sr Deposition	Precipitation	<sup>90</sup> Sr Deposition	Precipitation	<sup>90</sup> Sr Deposition	Precipitation
Anchorage, Alaska	0.0	8.5	0.0	6.5	–	15.9	–	29.7	0.0	60.5
Argonne, Illinois	0.1	18.6	0.1	33.4	0.1	26.9	0.0	29.5	0.2	108.4
Birmingham, Alabama	0.1	50.6	0.0	22.2	0.0	14.7	0.0	31.7	0.1	119.3
Chester, New Jersey	0.0	23.2	0.1	44.7	0.1	39.2	0.1	39.3	0.2	146.4
Cold Bay, Alaska	0.0	20.3	0.0	14.7	0.1	29.5	0.0	31.1	0.1	95.5
Fairbanks, Alaska	0.0	3.4	0.0	5.6	0.1	25.9	0.1	12.1	0.2	47.1
Houston, Texas	0.0	31.4	0.0	26.0	0.0	22.0	0.0	21.8	0.0	101.2
Lihue, Hawaii	0.0	36.7	0.0	14.5	0.0	12.2	0.1	36.6	0.1	100.0
Mauna Loa, Hawaii	0.0	54.5	0.0	0.3	0.1	7.5	0.0	44.9	0.1	107.2
Miami, Florida	0.0	9.4	0.0	54.8	0.0	48.0	0.1	19.1	0.2	131.1
New York, New York	–	28.7	0.1	42.5	0.1	46.0	0.1	37.5	0.4	154.7
Nome, Alaska	0.1	5.4	0.0	10.8	0.2	27.0	0.1	13.2	0.3	56.3
Vermillion, South Dakota	0.0	5.5	0.0	28.7	0.0	20.6	0.0	6.0	0.1	60.7
West Los Angeles, California	0.1	16.7	0.1	5.3	0.1	0.1	0.0	4.1	0.2	26.2
Wooster, Ohio	0.0	16.5	0.1	28.0	0.0	43.5	0.0	36.9	0.1	124.8
Average	0.03	22.0	0.03	22.5	0.06	25.3	0.04	26.2	0.2	96.0

Source: DOE 1996e

<sup>a</sup>in Bq/m<sup>3</sup><sup>b</sup>in cm



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The background level of  $^{90}\text{Sr}$  in soils of the United States from global fallout will depend upon the historical transport and deposition inventory at that particular location. The mean regional background concentration of  $^{90}\text{Sr}$  in soils in proximity to the Los Alamos National Laboratory from 1974 to 1994 was  $320 \pm 250$  pCi/kg dry weight soil (Fresquez et al. 1996b). This value has decreased with time due to radioactive decay of  $^{90}\text{Sr}$ . The range of concentrations for  $^{90}\text{Sr}$  in soils and sediments at 91 wastes sites located at the 18 DOE facilities around the United States was 0.02–540,000 pCi/kg (DOE 1992).

#### 6.4.4 Other Environmental Media

The range of concentrations of strontium in fruits and vegetables is summarized in Table 6-6. The highest concentrations are observed in leafy vegetables, such as cabbage (64.2 mg/kg Sr) (Barnes 1997; USGS 1980). The range of concentrations of  $^{90}\text{Sr}$  in food stuffs is summarized in Table 6-7. The highest concentrations were observed in fresh vegetables (8.8 pCi/kg dry weight=0.33 Bq/kg dry weight) and dry beans (15.9 pCi/kg dry weight=0.59 Bq/kg dry weight) (Eisenbud 1987). The U.S. Food and Drug Administration Radionuclides in Foods program monitors radionuclides (e.g.,  $^{90}\text{Sr}$ ) in the food supply as part of the Total Diet Study (TDS). For the years 1994 and 1995, about 60 foods with historically high  $^{90}\text{Sr}$  levels were analyzed (Capar and Cunningham 2000).  $^{90}\text{Sr}$  was detected in about 65% of these foods. The greatest concentration was in mixed nuts at 2 Bq/kg (50 pCi). Approximately 200 reactor-survey food test portions, including raw vegetables, food crops (primarily fruits), fish, and milk, were collected in the vicinities of 33 nuclear reactors (Cunningham et al. 1994). Ninety-four percent of the reactor-survey food test portions had  $^{90}\text{Sr}$  activities between 0 and 0.74 Bq/kg (0 and 20 pCi), and 6% had activity concentration between 0.74 and 7.4 Bq/kg (20 and 200 pCi/kg). The EPA ERAMS program monitors ambient concentrations of  $^{90}\text{Sr}$  in pasteurized milk at 42 sites in major population centers, and is used to assess trends and anomalies in concentrations. Table 6-8 summarizes pasteurized milk samples for the period of July 1997 (EPA 2000c). The average concentration of  $^{90}\text{Sr}$  in pasteurized milk during this period for the 42 sites was 0.9 pCi/L (33 mBq/L). Sites with above average levels of  $^{90}\text{Sr}$  in pasteurized milk were observed at (listed in order of decreasing activity of  $^{90}\text{Sr}$ ): Minot, North Dakota; Grand Rapids, Michigan; Spokane, Washington; Cleveland, Ohio; Cincinnati, Ohio; Memphis, Tennessee; St. Paul, Minnesota; Chicago, Illinois; Detroit, Michigan; San Francisco, California; Baltimore, Maryland; and Wilmington, Delaware. Dietary intake of  $^{90}\text{Sr}$  peaked in 1965 at 1.1 Bq/day (30 pCi/day), during a period of atmospheric testing of nuclear weapons, and has continued to decline to <0.05 Bq/day (<1.2 pCi/day) after 1987 (Cunningham et al. 1989). Dietary intake of  $^{90}\text{Sr}$  in the United States from 1961 to 1991 is illustrated in Figure 6-3.

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**Table 6-6. Concentration of Strontium in Fruit Juices and Produce**

Fruit juice and produce	Average liquid concentration (µg/L) <sup>a</sup>	Average solid concentration (ppm) <sup>b</sup>
Apple		13.58
Apple juice	0.1271	
Banana	0.1297	
Bean:		
Dry		6.63
Snap		21.7
Blackberry	0.2619	
Boysenberry	0.9523	
Cabbage		64.17
Corn:		
Sweet		0.416
Cucumber		24
Currant:		
Red	1.251	
Grape:		
American		25.6
Concord	0.3661	
European		38.4
Red	0.1086	
White	0.6318	
Kiwi	1.744	
Lemon products:		
Lemon	0.0986	
Bottled	0.5334	
Lemonade	0.1653	
Lettuce		22.26
Lime	0.3464	
Mango	0.5121	
Orange		25.56
Orange juice		
Brazilian	0.0417	
California	0.5368	
Florida	0.0933	
Navel	0.5209	
Pineapple	0.1612	

## 6. POTENTIAL FOR HUMAN EXPOSURE

**Table 6-6. Concentration of Strontium in Fruit Juices and Produce (*continued*)**

Fruit juice and produce	Average liquid concentration (µg/L) <sup>a</sup>	Average solid concentration (ppm) <sup>b</sup>
Papaya	1.690	
Peach		3.082
Pear	0.5912	
Pineapple	0.0604	
Potato		2.562
Raspberry	2.232	
Strawberry	0.3001	
Tangerine	0.0828	
Tomato		9.96
Tomato sauce	0.8894	

<sup>a</sup>Barnes 1997<sup>b</sup>USGS 1980

Table 6-7. <sup>90</sup>Sr in the Human Diets During 1982<sup>a</sup>

Diet category	kg/year	g Ca/year	Percent yearly intake Ca	New York City			San Francisco		
				pCi <sup>90</sup> Sr/kg	pCi <sup>90</sup> Sr/year	Percent yearly intake <sup>90</sup> Sr	pCi <sup>90</sup> Sr/kg	pCi <sup>90</sup> Sr/year	Percent yearly intake <sup>90</sup> Sr
Dairy products	200	216.0		3.2	641		1.0	200	
			58			32			21
Fresh vegetables	48	18.7		8.8	422		2.4	116	
Canned vegetables	22	4.4		5.4	119		2.9	64	
Root vegetables	10	3.8		3.4	34		3.8	38	
Potatoes	38	3.8		2.3	88		2.1	79	
Dry beans	3	2.1		15.9	48		7.9	54	
			9			36			36
Fresh fruit	59	9.4		2.6	152		1.3	77	
Canned fruit	11	0.6		1.1	12		0.8	9	
Fruit juice	28	2.5		1.7	48		1.4	40	
			3			11			13
Bakery products	44	53.7		3.0	131		1.9	84	
Flour	34	6.5		4.5	153		3.5	119	
Whole grain products	11	10.3	6.2	69			2.9	32	

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Macaroni                      3                      0.6                      2.4                      7                      2.3                      7

**Table 6-7. <sup>90</sup>Sr in the Human Diets During 1982<sup>a</sup> (*continued*)**

Diet category	kg/year	g Ca/year	Percent yearly intake Ca	New York City			San Francisco		
				pCi <sup>90</sup> Sr/kg	pCi <sup>90</sup> Sr/year	Percent yearly intake <sup>90</sup> Sr	pCi <sup>90</sup> Sr/kg	pCi <sup>90</sup> Sr/year	Percent yearly intake <sup>90</sup> Sr
Rice	3	1.1		0.6	2		0.8	2	
			20			18			25
Meat	79	12.6		0.4	35		0.4	31	
Poultry	20	6.0		0.3	6		0.3	5	
Eggs	15	8.7		0.6	10		0.6	8	
Fresh fish	8	7.6		0.2	1		0.1	1	
Shell fish	1	1.6		0.2	<1		0.7	1	
			10			3			5
Yearly intake		370 g			1978 pCi			967 pCi	
Intake					54 pCi/g Ca			2.6 pCi/g Ca	
					(54 pCi/day)			(2.6 pCi/day)	

Source: DOE 1984

<sup>a</sup>1 pCi=37 mBq (conversion factor)

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**Table 6-8.  $^{90}\text{Sr}$  in Pasteurized Milk in July 1997**

State <sup>a</sup>	City	$^{90}\text{Sr}$ (pCi/L)
AL	Montgomery	0.98
CA	Los Angeles	0.66
CA	Sacramento	0.26
CA	San Francisco	1.24
CO	Denver	0.41
CT	Hartford	1.31
DE	Wilmington	1.00
FL	Tampa	0.59
GA	Atlanta	0.56
HI	Honolulu	0.38
IA	Des Moines	0.40
IL	Chicago	1.38
IN	Indianapolis	0.96
KY	Louisville	0.20
MA	Boston	0.77
MD	Baltimore	1.06
MI	Detroit	1.34
MN	Grand Rapids	1.78
MN	St. Paul	1.44
MO	Kansas City	1.14
MS	Jackson	—
NC	Charlotte	1.25
ND	Minot	2.12
NJ	Trenton	0.75
NM	Albuquerque	0.53
NV	Las Vegas	0.20
NY	Buffalo	0.75
NY	Syracuse	0.94

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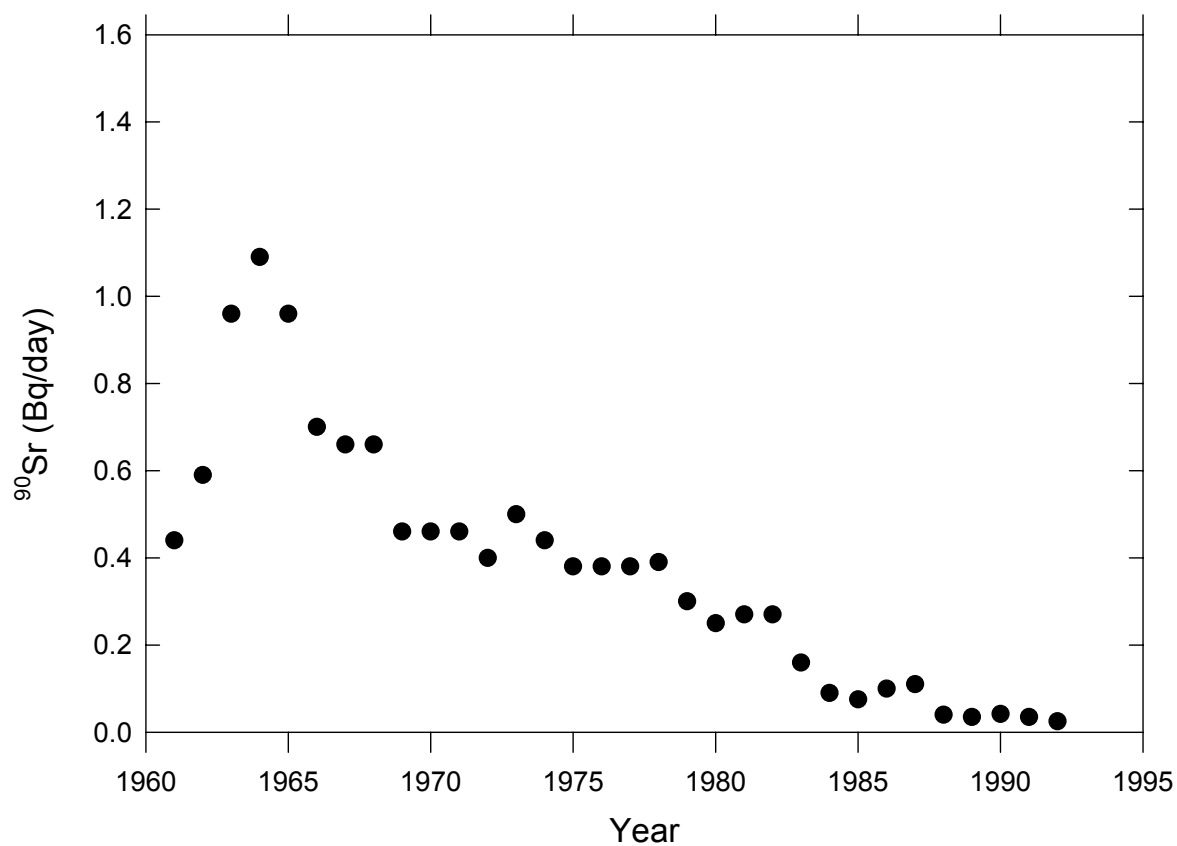
**Table 6-8.  $^{90}\text{Sr}$  in Pasteurized Milk in July 1997 (*continued*)**

State <sup>a</sup>	City	$^{90}\text{Sr}$ (pCi/L)
OH	Cincinnati	1.60
OH	Cleveland	1.60
OR	Portland	0.79
PA	Philadelphia	0.84
PA	Pittsburgh	0.23
PC	Cristobal	0.27
PR	San Juan	0.51
SC	Charleston	0.73
TN	Memphis	1.54
TX	Austin	0.29
TX	Ft. Worth	0.50
VA	Norfolk	0.89
VT	Burlington	1.10
WA	Seattle	0.49
WA	Spokane	1.71

<sup>a</sup>Post office state abbreviations used

Source: EPA 2000b

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**Figure 6-3. U.S. Daily Dietary Intake of  $^{90}\text{Sr}$ , 1961–1992**

Source: Cunningham et al. 1994



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Sato et al. (1977) determined the concentration of strontium in tobacco leaves as 141  $\mu\text{g/g}$ . The average concentration of strontium in the ash of 12 brands of cigarettes was measured as 373  $\mu\text{g/g}$  (Iskander 1986). No significant difference was observed in the concentration of strontium in the cigarette filter before and after smoking (Sato et al. 1977). The ranges of concentrations of strontium in waste materials are: municipal solid waste (MSW) 11–35  $\mu\text{g/g}$ ; incineration fly ash 110–220  $\mu\text{g/g}$  (Lisk 1988); coal fly ash 30–7,600  $\mu\text{g/g}$ ; coal bottom ash 170–6,400  $\mu\text{g/g}$ ; flue-gas desulfurization by-products 70–3,000  $\mu\text{g/g}$ ; oil ash 50–920  $\mu\text{g/g}$ ; (Eary et al. 1990); and compost 260–420  $\mu\text{g/g}$  (Evans and Tan 1998).

**6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE**

The primary routes of human exposure to strontium are from inhalation of aerosols and ingestion of food and drinking water containing strontium. The intake of strontium, therefore, depends upon the concentration of strontium in air, drinking water, and in the food items that comprise a person's diet, which may be highly variable. The average concentration of strontium in urban air is about 20 ng Strontium/ $\text{m}^3$  (see Section 6.4.1). Assuming that an adult breathes approximately 20  $\text{m}^3$  of air per day, the inhalation exposure would be 400 ng Strontium/day. This value may be somewhat higher for persons living near sources of strontium emission. Workers employed at industrial facilities that produce, process, and use strontium and strontium compounds will have higher exposures. Similarly, strontium is taken into the body by ingestion of drinking water. Using the concentration of strontium in U.S. drinking water to be 1 mg/L (see Section 6.4.2), and the consumption rate as 2 L/day, the strontium intake from drinking water would be 2 mg/day. In a 1994 total diet study in the United Kingdom, the total dietary exposure to stable strontium was estimated at 1.3 mg/day (Ysart et al. 1999). Combining air, water, and diet exposures, the total estimated daily exposure to strontium is approximately 3.3 mg/day.

External exposure to  $^{90}\text{Sr}$  is not a concern because of minor emission of penetrating radiation from  $^{90}\text{Sr}$ . No estimate of the concentration of  $^{90}\text{Sr}$  in air is available (see Section 6.4.1). However, it is assumed that ambient concentrations of  $^{90}\text{Sr}$  in the atmosphere are small relative to exposures from water and diet. If the concentration of  $^{90}\text{Sr}$  in average U.S. drinking water is estimated as 0.1 pCi/L (4 mBq/L) or one radiochemical event per 5–10 minutes (see Section 6.4.2), and the consumption rate of drinking water by a normal adult is assumed to be 2 L/day, then the exposure from drinking water would be 0.2 pCi (7 mBq) per day. Since the inception of the TDS Radionuclides in Foods program in 1961, intake levels of  $^{90}\text{Sr}$  in food have steadily declined from a peak level in 1965 of 1.1 Bq/day (30 pCi/day), to below 0.2 Bq/day (5 pCi/day) (Cunningham et al. 1989). A DOE Environmental Measurements Laboratory

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study estimated the average dietary intake of  $^{90}\text{Sr}$  from 19 diet categories for individuals living in the urban areas of New York City and San Francisco. Table 6-6 summarizes the data from this study (DOE 1984). For both locations, vegetables accounted for more than a third of the yearly dietary intake of  $^{90}\text{Sr}$  at 36%. In the vegetable group, fresh vegetables were the largest contributors of  $^{90}\text{Sr}$  dietary intakes. The next largest contributor of  $^{90}\text{Sr}$  was grains and dairy products. Using a conservative estimate of total dietary exposure for  $^{90}\text{Sr}$  of 5 pCi/day (0.19 Bq/day) and drinking water exposure of 0.2 pCi/day (7 mBq/day), the total estimated daily exposure to strontium is approximately 5.2 pCi/day (0.19 Bq/day). Current population exposure levels to  $^{90}\text{Sr}$  will be lower than this value as a result of decreasing concentrations of  $^{90}\text{Sr}$  in the environment. However, this value may be somewhat higher for persons living near sources of  $^{90}\text{Sr}$ , such as DOE facilities; and for workers employed at government facilities that produce, process, and use  $^{90}\text{Sr}$  and  $^{90}\text{Sr}$  waste compounds.

Table 6-9 summarizes measurements of concentrations of strontium in human tissues and body fluids resulting from consumption of food and water and from natural background sources (Iyengar et al. 1978). These are nonoccupationally exposed populations. The highest concentrations of strontium are in the bones and teeth (Iyengar et al. 1978). The distributions of  $^{90}\text{Sr}$  in the body are significantly different for males and females. As expected, the highest concentrations of  $^{90}\text{Sr}$  are measured in the boney tissue. Males averaged and females averaged 10.4 and 65 pCi/kg (0.38 and 2.4 Bq/kg) wet weight, respectively. Males had a much higher concentration of  $^{90}\text{Sr}$  in the muscular tissue compared to females. The heart and psoas muscles had respective concentrations of  $^{90}\text{Sr}$  for men averaging 13.9 and 18.7 pCi/kg (0.51 and 0.69 Bq) wet weight versus respective concentrations of 7.4 and 1.9 pCi/kg (0.27 Bq/kg and 70 mBq/kg) wet weight for females (Baratta and Ferri 1966).

Strontium can be released into the atmosphere as a result of glass manufacturing. In one study, the median ambient air concentration of strontium that both art glass makers and formers were chronically exposed was 0.1 mg Strontium/ $\text{m}^3$  (Apostoli et al. 1998). A National Occupational Exposure Survey conducted by NIOSH during 1981–1983 estimated the number of workers potentially exposed to strontium compounds in the workplace, e.g., strontium chloride (8,289), strontium fluoride (5,607), strontium hydroxide (385), and strontium nitrate (1,895) (NOES 1983). Workers engaged in nuclear fuel cycle operations, such as the handling of radioactive strontium wastes, decontamination and decommissioning workers, contaminated soils, and waters may be potentially exposed to radioactive strontium. A case of accidental inhalation and dermal exposure to strontium titanate contaminated with  $^{90}\text{Sr}$  used for lightning rods was recorded, which resulted in an exposure of approximately  $10^5$  Bq (2.7 mCi) to the workers (Navarro and Lopez 1998).

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**Table 6-9. Strontium Concentrations in Human Body Fluids and Tissues**

Sample	Units <sup>a</sup>	Mean	Range
Blood	µg/L	27	—
Bone	µg/g	138	63–281
Brain	µg/g	0.08	—
Dental plaque	µg/g	48	<0.5–1,880
Erythrocytes	µg/L	7.2	—
Feces	µg/day	1.5	—
Hair	µg/g	4.2	0.75–10.8
Kidney	µg/g	0.1	—
Liver	µg/g	0.15	—
Lung	µg/g	0.38	—
Milk	µg/L	20	17–295
Muscle	µg/g	0.05	—
Nails (finger)	µg/g(dry weight)	—	0.43–0.86
Plasma or serum	µg/L	40	10–70
Saliva	µg/L	11	8–63
Sweat	mg/7 hour	0.96	—
Tooth (dentin)	µg/g	115	14–286
Tooth (enamel)	µg/g	128	14–286
Urine	µg/L	—	<0.01–0.03

Source: Tsalev 1984

<sup>a</sup>Values are per wet weight unless otherwise noted.

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**6.6 EXPOSURES OF CHILDREN**

This section focuses on exposures from conception to maturity at 18 years in humans. Differences from adults in susceptibility to hazardous substances are discussed in 3.7 Children's Susceptibility.

Children are not small adults. A child's exposure may differ from an adult's exposure in many ways. Children drink more fluids, eat more food, breathe more air per kilogram of body weight, and have a larger skin surface in proportion to their body volume. A child's diet often differs from that of adults. The developing human's source of nutrition changes with age: from placental nourishment to breast milk or formula to the diet of older children who eat more of certain types of foods than adults. A child's behavior and lifestyle also influence exposure. Children crawl on the floor, put things in their mouths, sometimes eat inappropriate things (such as dirt or paint chips), and spend more time outdoors. Children also are closer to the ground, and they do not use the judgment of adults to avoid hazards (NRC 1993a).

Specific information on the exposure of children to radiostrontium is limited. As for adults in the general population, small exposures occur from normal ingestion of food and drinking water and inhaling air. These exposures may be higher in areas near nuclear fuel processing sites and hazardous waste sites containing radiostrontium. Future accidental exposures could potentially occur from nuclear weapons detonation and consequent contamination of air, water, and food.

Children typically ingest a higher percentage of dairy products compared to adults. Levels of  $^{90}\text{Sr}$  in body tissues tend to increase with age (Glowiak and Pacyna 1978). In a study in the Soviet Union between 1959 and 1971, children were reported to have elevated levels of  $^{90}\text{Sr}$  in bone tissue between the ages of 1 and 4 years (Marei et al. 1976). The elevated levels of  $^{90}\text{Sr}$  for children of this age were determined to be a direct result of diet, primarily from  $^{90}\text{Sr}$  contaminated cow's milk. In a 1978 study in Poland, females between 0 and 20 years of age had the highest level of  $^{90}\text{Sr}$  accumulation in the gonad tissues for all age levels (Glowiak and Pacyna 1978). No explanation as to a cause for this accumulation was provided. No additional information is available on whether children differ from adults in their weight-adjusted intake of strontium. There is no information on  $^{90}\text{Sr}$  levels in amniotic fluid, meconium, cord blood, neonatal blood, or breast milk.

At hazardous waste sites, radiostrontium that is found in excess of natural background levels is most likely to be in soil and presents a special hazard for young children. Hand-to-mouth activity resulting in inadvertent soil consumption or intentional consumption of soil (pica behavior) will result in oral

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exposure to radiostrontium. Young children often play close to the ground and frequently play in dirt, which increases their dermal exposure to radiostrontium in dust and soil. The degree of hazard in each case depends on the form of strontium present at the waste site.

Compared to adults, the potential for radiostrontium exposure is greater for children who consume foods (e.g., milk, grains) produced in areas with elevated concentrations of radiostrontium in the soil and for children with elevated concentrations of radiostrontium in their drinking water. Children are more likely to be exposed to  $^{90}\text{Sr}$  in cow's milk produced in contaminated areas. Table 6-8 summarizes pasteurized milk samples in the United States for July 1997 (EPA 2000c). The average concentration of  $^{90}\text{Sr}$  in pasteurized milk during this period was 0.9 pCi/L (33 mBq/L).

Other home exposures are unlikely since no household products or products used in crafts, hobbies, or cottage industries contain significant amounts of radiostrontium. Radiostrontium exposure to children from parents' work clothes, skin, hair, tools, or other objects from the workplace is possible if the parent is exposed to radiostrontium at work. However, no specific cases of home contamination with radiostrontium were located in the literature.

**6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES**

Cigarettes and tobacco leaves are known to contain strontium, and individuals who smoke may be exposed to higher levels of strontium. Strontium has been found in the tobacco leaves and ash of cigarettes at average levels of 141 and 373 mg/kg, respectively (Iskander 1986).

The potential for  $^{90}\text{Sr}$  exposure is greater for individuals who consume foods grown in areas with elevated concentrations of  $^{90}\text{Sr}$  in soil, and for individuals with elevated concentrations of  $^{90}\text{Sr}$  in drinking water. Industries where higher exposures to  $^{90}\text{Sr}$  are known to occur include nuclear weapons test sites, nuclear weapons production, and nuclear reactors facilities. Populations with potentially high exposure include DOE employees involved in heavy construction, chemical processing, and fabrication.

Populations with a relatively short food chains (e.g., arctic peoples) and a higher per capita consumption of country foods that have elevated levels of contamination from radionuclides, will have a higher exposure to  $^{90}\text{Sr}$  (Barrie et al. 1992). Caribou or reindeer feeding on arctic vegetation are more likely to accumulate higher body burdens of  $^{90}\text{Sr}$  in edible tissues than other herbivorous animals with less restrictive diets (Witkamp 1966). Concentrations of  $^{90}\text{Sr}$  in caribou meat per gram of calcium were high

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(150 pCi/g Ca) compared with those of Alaskan-grown cabbage (6 pCi/g Ca) and potatoes (8 pCi/g Ca), marine fish (5 pCi/g Ca), and whale meat (1 pCi/g Ca). Thus, arctic peoples, who depend on caribou and reindeer for sustenance, will have a factor of 30 higher body burden of  $^{90}\text{Sr}$ , compared to other people who consume a more varied diet (Witkamp 1966).

## 6.8 ADEQUACY OF THE DATABASE

Section 104(i)(5) of CERCLA, as amended, directs the Administrator of ATSDR (in consultation with the Administrator of EPA and agencies and programs of the Public Health Service) to assess whether adequate information on the health effects of strontium is available. Where adequate information is not available, ATSDR, in conjunction with the National Toxicology Program (NTP), is required to assure the initiation of a program of research designed to determine the health effects (and techniques for developing methods to determine such health effects) of strontium.

The following categories of possible data needs have been identified by a joint team of scientists from ATSDR, NTP, and EPA. They are defined as substance-specific informational needs that if met would reduce the uncertainties of human health assessment. This definition should not be interpreted to mean that all data needs discussed in this section must be filled. In the future, the identified data needs will be evaluated and prioritized, and a substance-specific research agenda will be proposed.

### 6.8.1 Identification of Data Needs

**Physical and Chemical Properties.** Relevant data on the physical and chemical properties of strontium and strontium compounds are available in the literature (see Chapter 4).

**Production, Import/Export, Use, Release, and Disposal.** Data regarding the past and present production and import/export volumes for strontium are available. The uses of strontium and strontium compounds are well known. Since strontium is not covered under Superfund Amendments and Reauthorization Act (SARA), Title III, manufacturers and users are not required to report releases to the EPA's Toxic Release Inventory. The disposal of radiostrontium and radiostrontium contaminated wastes is governed by the U.S. Nuclear Regulatory Commission (NRC) regulations, and releases of radiostrontium and radiostrontium contaminated wastes are governed by NRC and EPA regulations.

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**Environmental Fate.** Information about the fate of  $^{90}\text{Sr}$  in air, water, soils, and sediments is available. Additional information on the environmental fate of  $^{90}\text{Sr}$  in different forms of mixed waste may be beneficial. Studies investigating mixed waste matrixes may be useful information for accessing the current and potential risk of the storage of liquid HLW in buried underground tanks. Mixed waste forms that pose the highest potential risk include mixtures such as metals-radiostrontium, metals-radiostrontium-organic acids, metals-radiostrontium-complexing agents, and metals-radiostrontium-ketones (DOE 1992).

**Bioavailability from Environmental Media.** The absorption and distribution of strontium as a result of inhalation, dermal, or oral exposures have been discussed in Sections 3.4.1 and 3.4.2. No information on the bioavailability of strontium and radiostrontium from environmental media is available.

**Food Chain Bioaccumulation.** Data concerning levels of strontium in various foods are available, but dated. Data on food grown in contaminated areas are limited.

**Exposure Levels in Environmental Media.** Information about concentrations of strontium and  $^{90}\text{Sr}$  in air, water, soil, and food are available. However, updated information on the concentration levels in air, soil, and food may be useful. Specific monitoring of  $^{90}\text{Sr}$  in airborne particulates may also be beneficial. Reliable monitoring data for the levels of  $^{90}\text{Sr}$  in contaminated media at hazardous waste sites may be useful so that the information obtained on levels of  $^{90}\text{Sr}$  in the environment can be used in combination of the known body burden with strontium to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

**Exposure Levels in Humans.** The primary source of recent information on the occurrence of  $^{90}\text{Sr}$  in drinking water is the National Inorganics and Radionuclides Survey conducted by EPA. Better and more recent information on background levels in the environment (e.g., air, food, water, and soil) may be useful. Additional information on bioavailability of strontium and radiostrontium from environmental media is necessary.

**Exposures of Children.** Children may be exposed to strontium and radiostrontium in the same manner as adults in the general population (e.g., air, food, water). No information was available on unique exposure pathways for children (e.g., pica children, dermal). Better and more recent information on exposure levels to children may be beneficial. Child health data needs relating to susceptibility are discussed in 3.12.2 Identification of Data Needs: Children's Susceptibility.

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**Exposure Registries.** No exposure registries for strontium were located. This substance is not currently one of the compounds for which a subregistry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for subregistries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

**6.8.2 Ongoing Studies.**

The Federal Research in Progress (FEDRIP 2000) database provides additional information obtainable from a few ongoing studies that may fill in some of the data needs identified in Section 6.8.1. These studies are summarized in Table 6-10.



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**Table 6-10. Ongoing Studies on Environmental Effects of Strontium<sup>a</sup>**

Investigator	Affiliation	Study	Sponsor <sup>b</sup>
Chaney RL; Angle JS	Agronomy University of Maryland College Park, Maryland	Phytoavailability and bioavailability of heavy metals from heavy metal contaminated soil	USDA
Heit M	Environmental Measurements Laboratory New York, New York	Fallout radionuclides in deposition, diet, and bone	USDOE Energy Research
Meinhold C	National Council on Radiation Protection and Measurements Bethesda, Maryland	Development of recommendations on radiation protection and measurements	USDOE Energy Research
Sayler GS	University of Tennessee Center for Environmental Biotechnology Knoxville, Tennessee	On-line monitoring of aerobic bioremediation with bioluminescent reporter microbes	USDOE Energy Research
Unidentified	Idaho Operations Office (USDOE) University of Toronto	Microbial mineral transformations at the Fe(II)/Fe(III) redox boundary for solid Phase capture of strontium and other metal/radionuclide contaminants	USDOE Environmental Management

<sup>a</sup>Source: FEDRIP 2000

USDA = U.S. Department of Agriculture; USDOE = U.S. Department of Energy